

Physics-Based Parameterizations of Air-Sea Fluxes at High Winds

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LONG-TERM GOALS

The long term goal of this project is to provide a new set of parameterizations of air-sea fluxes, which can be used as boundary conditions for high-resolution numerical models of ocean, atmosphere, and coupled ocean/atmosphere systems. The new parameterizations will be constructed based on physical processes of the exchange of mass, momentum, heat, moisture, energy at the interface between the ocean and the atmosphere, and will be valid for the whole range of wind speeds.

OBJECTIVES

It is clear intuitively that at high wind speeds breaking waves become increasingly important to air-sea interaction. But the role of these breaking waves on air-sea fluxes is at present almost completely unknown. In this project we develop recent understanding of surface wave processes, and in particular breaking waves and their statistics, to develop a framework for accounting for wave breaking in air-sea fluxes in high winds. The specific objectives are:

- To develop a theoretical model for the statistics of breaking wave coverage, based on the dynamics of the surface waves.
- To use these statistics to formulate a methodology for accounting for the exchange of momentum and kinetic energy between the atmosphere and ocean that results from the breaking waves.
- To integrate this methodology into the framework developed by Makin and co-workers [Makin et al. 1995, Makin and Kudryavtsev 1999] for air-sea exchange for non-breaking waves.
- To then develop a model for transfer of scalars, such as heat and moisture, that accounts for both breaking and non-breaking waves.
- To validate, where possible, the components of these models against observational data.
- To clarify limitations of bulk parameterizations and identify improvements.

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APPROACH

The first step is to validate our recent model results of the equilibrium range of surface wave spectra [Hara and Belcher 2001] and breaking wave statistics [Belcher and Hara 2001], using the new observational data in collaboration with other PIs. We clarify the range of wavenumbers where our model is applicable.

We develop a model of momentum flux (wave-induced stress and turbulent stress), mean wind profile, and TKE budget in the atmospheric surface layer at high sea states including the contributions from breaking waves. We begin by assuming that the total air-sea momentum flux at high winds is a sum of three contributions from: the skin friction; non-breaking waves; and breaking waves. The momentum flux due to non-breaking waves is estimated following the methodology of Makin and Kudryavtsev [1999]. In the absence of breaking waves, the total wind stress is assumed to be constant in height and is written as the sum of the turbulent stress and the wave-induced stress,

$$\tau_{tot} = \rho_a u_*^2 = \tau_w(z) + \tau_t(z) \quad (1)$$

where z is a vertical coordinate. The eddy viscosity parameterization of the wind profile $u(z)$ is expressed as

$$\tau_t(z) = \rho_a K \frac{\partial u}{\partial z}, \quad K = \kappa u_* z \left(\frac{\tau_t(z)}{\tau_{tot}} \right)^{\frac{1}{4}}. \quad (2)$$

In the presence of breaking waves we perform the same calculation by substituting τ_{tot} and u_* by $\tilde{\tau} = \tau_{tot} - \tau_b$ and $\tilde{u}_* = \sqrt{\tilde{\tau} / \rho_a}$ where τ_b is the stress due to breaking waves. The additional momentum flux due to breaking waves τ_b is estimated by simply integrating the drag due to breaking wave crests;

$$\tau_b = \int_0^\infty \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \rho_a C_b \left[u(z = \frac{\pi}{k}) \right]^2 \Lambda(k, \theta) \beta_\Lambda k^2 d\theta dk \quad (3)$$

Here, $\Lambda(k, \theta)$ is the breaking wave statistics, C_b is the drag coefficient, and β_Λ is a constant corresponding to average slope of breaking waves. Using the model results we investigate at what wind speed the momentum flux supported by breaking waves exceeds that supported by non breaking waves and viscosity. We also study how the sheltering effect is modified for the forcing of short waves, how the breaking statistics and the drag coefficient estimates are affected, and how the energy in the 1d wave boundary layer is partitioned between energy in the wave-induced motions and the turbulent motions.

These dynamical models of the air flow in the atmospheric surface layer are used as a basis for modeling effects of breaking waves on transfer of scalars, such as heat and moisture, in the wave boundary layer. There are two distinct ways that the surface waves affect scalar transfer. Firstly, the transfer of scalars is controlled by turbulence actually at the wavy surface, and so it is the local turbulent stress that controls scalar transfer. Using our new model of the momentum exchange that accounts for the breaking waves we obtain the local turbulent stress and estimate the scalar transfer.

Secondly, the breaking waves induce air flow separation, which also affects scalar transfer in the vicinity of the separation region in the lee of the breaking wave. Some of the fluid dynamical mechanisms involved in transfer between surface waves and the atmosphere are similar to the mechanisms that control transfer over static rigid ‘waves’ (i.e. hills!), as reviewed recently by Belcher and Hunt [1998]. Hewer and Wood [1998] have shown how air flow separation can significantly change transfer of scalars over hills and we plan to use their results in formulating our model.

New knowledge gained from our process studies is used to develop new flux parameterizations in the atmosphere. An important question to be addressed here is how the presence of breaking waves affects the air-sea fluxes in realistic oceanic conditions. Since the breaking wave statistics are expected to depend on the stage of wave field development, we examine three cases, i.e., with mature seas, with developing seas (parameterized in terms of the wave age), and with more complicated wave field - using the observed wave field. We validate the model results of the total wind stress (drag coefficient), wind profile, heat and humidity flux, and the TKE flux against the new field observations. By making comparisons in conditions with increasing breaking wave events we are able to test the hypothesis of the non-breaking wave contribution first and then that of the breaking wave contribution at higher sea states.

We quantify the fluxes from the atmosphere and surface waves to the oceanic wave boundary layer. Once these fluxes have been estimated, we study the overall energy budget inside the wave boundary layer, i.e., the balance among the total kinetic energy injected into the water column from breaking waves and surface viscous shear, the total energy flux at the lower edge of the wave boundary layer, and the total viscous dissipation inside the water column; the last quantity can be compared with recent measurements by Terray et al. (1996) as well as new data from CBLAST. We then develop a dynamical model of the wave boundary layer. We first formulate the momentum, mean energy, and TKE equations in the wave boundary layer including these fluxes. The complexity here is that the viscous fluxes take place at the water surface, while the fluxes from surface waves take place across the depth of the wave boundary layer. We use similarity arguments as the corner stone of this part of the model: breaking waves are self-similar regardless of their scales. Hence, we use measurements of the lifecycle of turbulence from single breaking waves (e.g. Rapp and Melville 1990), which seems to resemble grid stirred turbulence (Thompson & Turner 1975). This lifecycle structure can then be integrated over all breaking waves to yield the vertical structure of the ocean wave boundary layer. Ultimately, we predict the vertical profiles of the mean current, TKE, and TKE flux across the wave boundary layer.

New knowledge gained from our process study is used to develop new parameterizations of fluxes into the surface layer of the ocean. The model results are compared with the new observations of subsurface currents/turbulence under CBLAST. Finally, we investigate whether it is necessary to explicitly include the surface wave information in the flux estimations as input to ocean/atmosphere numerical models. We use both the observed surface wave fields during CBLAST as well as simulated wave fields with a simple set of wave parameters to examine the sensitivity of the air-sea fluxes to different surface wave conditions. In particular we address how well the bulk parameterization works in general at high winds, when the bulk parameterization fail, and how much we can improve the flux estimates if we explicitly include the surface wave field.

These tasks are performed by the two PIs, and one graduate student at URI. Although all the proposed tasks will be performed under close collaboration between the two PIs, SEB is mainly responsible for

the theoretical model development of the TKE budget and the heat and humidity fluxes in the atmospheric wave boundary layer, and the theoretical model of the oceanic wave boundary layer. TH is mainly responsible for the theoretical model development of the momentum flux in the atmospheric wave boundary layer and all aspects of the model-data comparisons.

WORK COMPLETED

We have initiated the validation of the model of equilibrium surface wave spectra using existing data set. We have also started to construct a model of momentum flux (wave-induced stress and turbulent stress), mean wind profile, and TKE budget in the atmospheric surface layer.

RESULTS

Our preliminary results show that, in the absence of breaking waves, the drag coefficient and the equivalent surface roughness are mainly determined by two parameters, namely, the wave age and the sheltering wave age. The former quantity determines the width (in wavenumber) of the equilibrium range, while the latter quantity determines the level of the equilibrium wave spectrum. We are currently validating this result against existing field observations.

IMPACT/APPLICATIONS

This program of work promises a one dimensional (1d) model of the atmospheric and oceanic boundary layers in the vicinity of the air--sea interface that accounts for both breaking and non-breaking waves. The model will, given the ten meter wind speed, temperature and humidity and surface wave parameters, produce wave breaking statistics, wind and current profiles, fluxes and flux profiles and the turbulent kinetic energy budgets through the 1d air and water wave boundary layers. These results may be used as a basis for any future modeling efforts of ocean-atmosphere interaction processes.

TRANSITIONS

The results from this project are used to develop a new set of physics-based parameterizations of air-sea fluxes, which are valid for the whole range of wind speeds and can be used as boundary conditions for high-resolution numerical models of ocean, atmosphere, and coupled ocean/atmosphere systems.

RELATED PROJECTS

TH has an ongoing NSF project (2000-2003) to address the air-sea momentum flux at high sea. This NSF project is a subset (atmospheric wave boundary layer only) of this ONR project and therefore these two projects will be fully integrated. TH's main contribution to this ONR project will be in Year 4 and 5 (2004-2005).

New knowledge gained from our study will be incorporated in coupled atmosphere-wave-ocean numerical models under another ongoing NSF project (2000-2003) by TH and his colleagues. Current numerical wave models are not capable of predicting accurately short wind waves at frequencies much higher than the spectral peak. Instead they patch a parameterized form of spectra. More accurate information about short wind wave spectra and their breaking statistics resulting from this study will

improve the accuracy of the numerical wave prediction and will thus enhance the performance of coupled numerical models.

SEB is just beginning a project funded by the Leverhulme Trust (a UK charity that funds fundamental scientific research) into the dynamics of Langmuir turbulence in the ocean mixed layer. The aim is to develop understanding of the dynamical processes that determine the lifecycle of streamwise vortices in the ocean mixed layer. This will be done by developing a large eddy simulation of the ocean mixed layer that includes the dynamical effects of waves on the turbulence via the Stokes drift. In addition the model will account for the turbulence injected into the water column from breaking waves. Hence this Langmuir turbulence project will benefit from the parameterization of the oceanic wave boundary layer developed in the work proposed here.

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